CHAPTER 2

BASIC RADAR SYSTEMS

LEARNING OBJECTIVES

Upon completing this chapter, you should be able to do the following:

1. Describe the two types of energy transmission used by radar systems.

2. Describe the different seaming techiques used in radar systems.

3. Describe the major components in today's radar transmitters.

4. List the basic design requirements of an effective radar receiver.

INTRODUCTION

The two basic types of radar systems, pulse radars and continuous-wave radars, use pulse and continuous-wave energy transmission. As a Fire Controlman, you need to know how these systems work. This chapter discusses radars, scanning methods, transmitters, and receivers in detail.

For further information on radar systems, refer to *Microwave Principles*, Module 11, Navy Electricity and Electronics Training Series, NAVEDTRA 172-11-00-87; and *Radar Principles,* Module 18, Navy Electricity and Electronics Training Series, NAVEDTRA 172-18-00-84.

RADAR SYSTEMS

This section discusses the two types of pulse radars and the two types of continuous-wave radars.

PULSE-RADAR SYSTEMS

The pulse-radar systems include the basic pulse radar and the pulse-Doppler radar.

Basic Pulse-Radar System

The signal of a basic pulse-radar system is generated by the transmitter and is radiated into space by the antenna. Intermediate frequencies from 30 to 60 MHz are commonly used because signal handling is easier to accomplish at the lower frequencies than at the transmitter frequencies.

The duplexer enables the use of a single antenna to transmit and receive the radar signal. The return echo signal is then mixed with a local oscillator (LO) signal to produce an intermediate frequency (IF) signal at a lower frequency than the transmitter.

The IF filter conditions the echo signal through amplifying and filtering extraneous signals. The IF signal is then sent to the second detector where the IF is converted to a lower frequency video signal. At that time, the video signal is processed for display by a video amplifier.

The display is usually a cathode-ray tube (CRT) that is monitored by an operator. The timer/synchronizer controls the repetition frequency of the transmitter. It can also provide a zero range start signal for the display device.

Basic pulse-radar systems are rather complex in their composition, but they all contain the same basic functional areas, with additional equipment included for specific purposes. For instance, a *search radar* requires additional circuitry to indicate antenna azimuth position coincident with a particular target echo. Additional circuitry might also be added to a search radar for moving-target indication (MTI) and to filter out stationary targets, landmasses, and clutter from weather and the sea state.

A *tracking radar,* such as a fire-control radar, requires additional circuitry to measure target range, azimuth, and elevation. Since circuitry is also required to keep the antenna pointed at the target, fire-control radars have ranging and angle tracking systems included. Figure 2-1 shows a basic pulse radar.

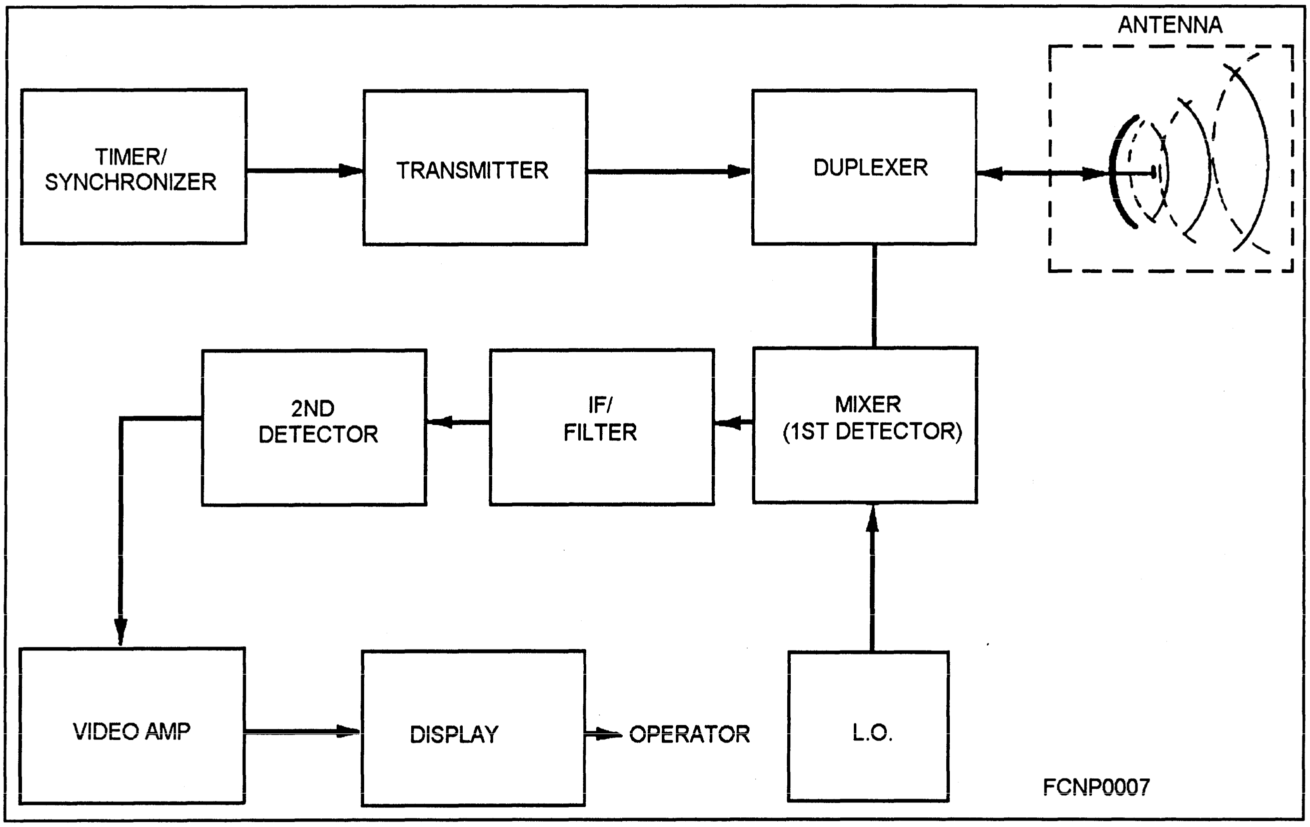

Figure 2-1.—Basic pulse radar.

Pulse-Doppler Radar System

A pulse-Doppler radar has certain advantages over a basic pulse radar or a continuous-wave radar. It can detect both stationary and moving targets and can also determine range. In addition, it can distinguish between two targets with the same radial velocity, but at different ranges. The radial velocity is the apparent speed that the target is closing on or going away from the radar.

Pulse-Doppler radar, however, has some disadvantages, too: blind target ranges and velocities, range and delivery ambiguities, and reduction in maximum range capabilities. These disadvantages can be compensated for by using additional circuitry.

A pulse radar's echo signal also contains velocity information in the Doppler frequency information, but the signal is not normally used by a basic pulse radar. By using the Doppler signal available on an echo signal, a basic pulse radar can detect a weak signal from a moving target in the presence of strong signals from large targets, such as landmasses and heavy seas.

Pulse-Doppler radars use the Doppler shift signal. These radars can detect an aircraft flying close to a hill or mountain where the strong landmass echo would block detection with a basic pulse radar. Circuitry in the pulse-Doppler radar normally would reject the stationary target, allowing easy detection of the weak signal from the moving target.

The ranging system of a pulse-Doppler radar is more complex than that of a pulse or a frequency-modulated, continuous-wave (FM-CW) radar. A pulse-Doppler radar senses both range and velocity by time-sharing its waveform between these functions. To detect a Doppler frequency from the target echo, most pulse- Doppler radars use a much higher pulse-repetition frequency (PRF) than basic pulse radars.

Higher PRF decreases the pulse-repetition time (PRT) between pulses, resulting in the possibility of a target echo returning at the time of the next transmission. This, in turn, results in a blind spot in the range. If the echo from the first pulse returns after the second pulse is transmitted, then a range ambiguity occurs.

The range blind spot and ambiguities can be compensated for by changing the PRF over a wide range. For example, the fire-control computer could adjust the radar PRF based on the expected range of a designated target. If the designation were for a target at 50 nmi (100 kyd), the PRF could be changed so that the second pulse would not occur until enough time had elapsed for the target echo to return for that range, plus an additional range interval for the acquisition and tracking gates. Varying the PRF over a wide range by computer control can resolve range ambiguities and blind ranges.

DOPPLER SHIFT THEORY.— A Doppler shift allows distinguishing between the target and the transmitter leakage. The amount of Doppler shift is determined by the radial velocity of the target since the radial velocity is the apparent speed that the target is closing on or going away from the radar.

A target can move in any direction and in a wide range of speed; therefore, the radial velocity can change considerably. If the target is moving at a 900 angle to the radar, then no Doppler shift is produced. However, if the target moves straight at or away from the radar, radial velocity will equal the actual target speed.

The amount of Doppler shift is also dependent on the wavelength resulting from the transmitter frequency. A target radial velocity that produces a specific Doppler shift at 5,000 MHz would produce twice as much at 10,000 MHz.

DOPPLER SHIFT DETECTION.— Pulse-Doppier radars can detect moving targets by the Doppler shift. Moving-target indication (MTI) is used primarily to detect moving targets with pulse-Doppler search radars.

Since stationary targets produce no Doppler shifts, the return signal echo has the same frequency and phase as the transmitted pulse. However, moving targets do produce Doppler shifts; therefore, the return signal echo has a different phase from that of the transmitted pulse.

To use this principle, pulse-Doppler radars must be able to compare the echo signal with a reference signal that is in phase (coherent) with the transmitted signal. A means of storing or controlling the transmitted phase is required to provide coherent detection.

One method uses a magnetron for the transmitter. This requires that the local oscillator be stable for a small fraction of a cycle during one pulse period. A sample of the transmitted and stable local oscillator (STALO) signals are fed to the coherent oscillator (COHO). This locks in the phase of the COHO until the next transmitter pulse. Figure 2-2 is a diagram of coherent MTI with a phase-locked COHO oscillator.

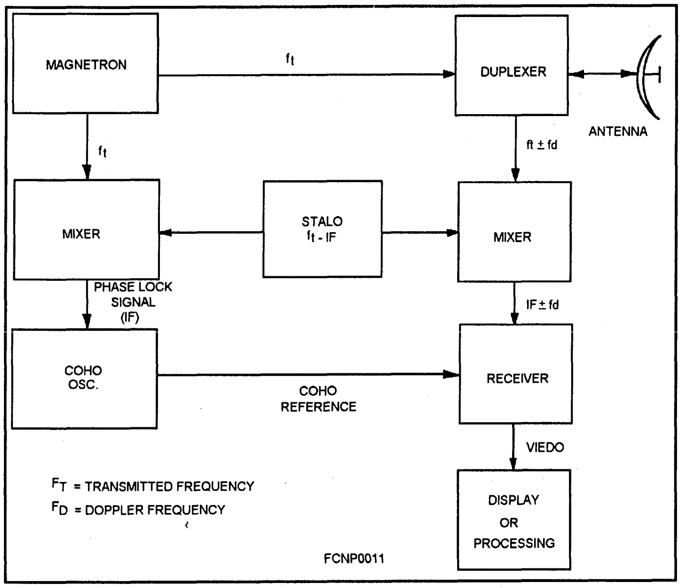

Figure 2-2.—Coherent MTI with a phase-locked COHO oscillator.

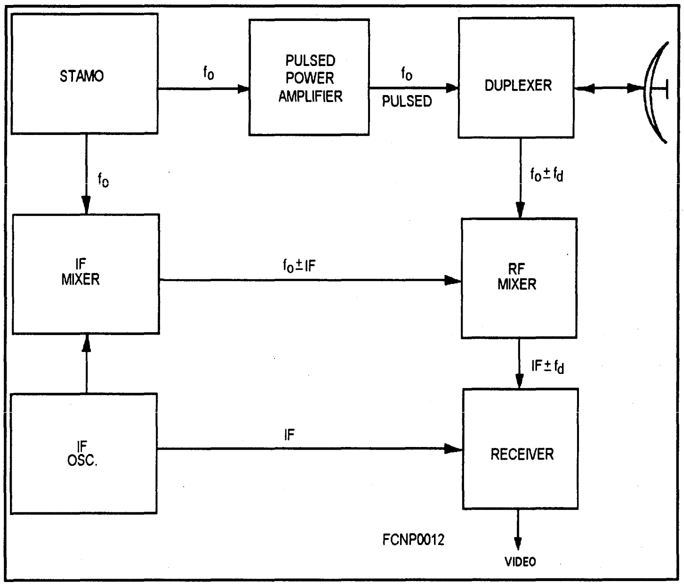

figure 2-3.—Coherent MTI with a STAMO oscillator.

With the development of power amplifier klystrons, traveling-wave tubes, and crossed-field amplifiers, a much better method evolved for coherency. A pulse-power amplifier fed by a stabilized master oscillator (STAMO) makes up the transmitted signal. The STAMO signal is mixed with the IF oscillator to provide an RF mixer input. The receiver then detects the Doppler shift and produces the video signal. The video signal from either type of coherent radar is usually bipolar (both positive and negative).

The bipolar video that is detected in a coherent receiver is caused by the phase and frequency differences of the return signals. Stationary targets, such as land, produce the same phase/frequency return on each pulse, whereas moving targets produce changing phase returns on each pulse. The MTI systems use pulse-to-pulse cancellation to suppress the stationary target returns by subtracting the previous return from the current return. Figure 2-3 is a diagram of a coherent MTI with a STAMO oscillator.

CONTINUOUS-WAVE RADAR SYSTEMS

The continuous-wave radar systems include the basic continuous-wave radar and the FM-CW radar.

Basic Continuous-Wave Radar System

A basic continuous-wave (CW) radar employs a continuous transmission that results in a continuous echo signal from a target. With a continuous echo signal, determination of the target range is impossible, since there is no distinguishing start and stop of the echo signal. Leakage from the transmitter into the receiver has the same form and could be classified as a target. If the target is moving radially with respect to the transmitter, then a shift in frequency occurs. This shift is called the *Doppler shift* or *Doppler frequency.*

Most CW radars use a separate antenna to receive, since there is no transmit rest period as in pulse radars. This also improves the isolation between the transmitted signal and the received echo signals.

Basic CW radars with a single antenna use a ferrite circulator to act as a duplexer. These circulators are limited to lower-power CW radars, because the amount of leakage from the transmitter to the receiver is about 20 to 30 decibels (dB) down from the transmitter power level. For a 1-watt transmitter, this would be 1 milliwatt of leakage. More leakage than this could easily damage the receiver.

The simple CW radar has the same basic components found in pulse radars; the main difference is the use of a separate antenna to receive and the use of filters to detect a Doppler shift. The filters are normally designed for the IF range, since working at the transmitter frequencies is more critical in the construction of circuits. The filters are set up to detect a particular narrow frequency band. The bands are set so they are adjacent to each other and cover the expected Doppler frequencies above and below the zero shift. The narrower the filter bandwidth, the more filters are required and the more discrete velocities can be determined within the receiver bandwidth.

With the basic CW radar, target range cannot be determined. However, a target can be tracked by the angle method. Angle resolution is determined the same way for both CW and pulse radars.

CW radars have an advantage over pulse radars when detecting moving targets in clutter. This is very useful when the clutter is caused by chaff, since detection is based on the Doppler frequency and not on a return pulse. With a simple CW radar, it is almost impossible to detect a stationary target because of clutter and leakage at the transmitter frequency. Moving targets are easily detected, but range determination is more difficult. A diagram of a basic CW radar is shown in figure 2-4.

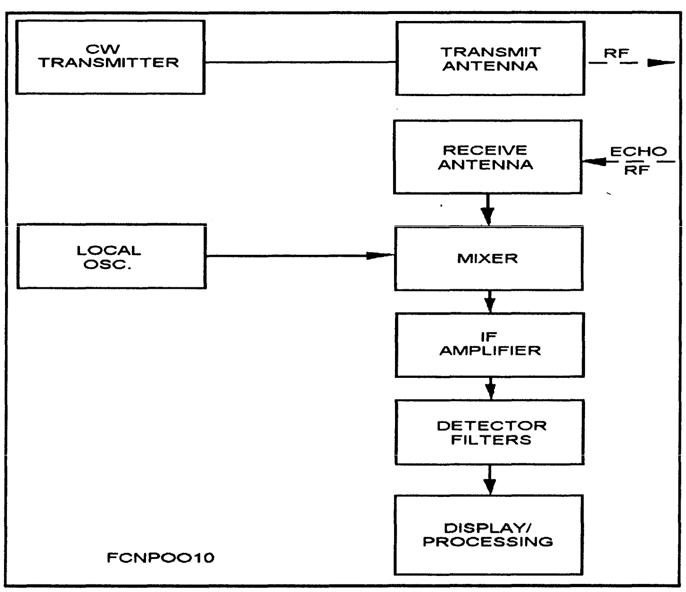

Figure 2-4.—Basic CW radar.

FM-CW Radar System

The limitation of being unable to determine target range with C W radars can be overcome by frequency modulating the transmitted signal. The resulting radar is the frequency-modulated, continuous-wave (FM-CW) radar.

The transmitter still transmits continuously, but the frequency is changed in a predetermined fashion. The modulation can be in the form of a sawtooth, triangular, sinusoidal, or other shape as long as it produces a frequency change of known rate.

SCANNING METHODS

For a radar to track a target, some means of keeping the radar beam pointed at the target is required. The radar system must be able to determine in which direction the radar beam must be moved so that the target remains in the center of the beam. A visual indication on the CRT can depict range and angle of the target in respect to the beam center. The operator can then move the beam by positioning the antenna center on the target. Today’s radar systems use computer-aided automatic tracking systems. Their two basic scanning methods are mechanical and electronic scanning.

MECHANICAL SCANNING

Mechanical scanning can be flexible in that the antenna can be moved in one of two desired patterns: (1) The feed horn can be moved relative to a fixed reflector, or (2) the reflector can be moved relative to a fixed feed horn. The most common mechanical scan technique used by fire-control radars is a movable feed horn relative to a fixed reflector, which is called *conical scanning.*

Included in mechanical scanning are nutation, nutating waveguide, and angle tracking.

Nutation

The nutation process is difficult to describe in words, but easy to demonstrate. Hold a pencil with both hands, one hand at the eraser end and the other hand at the point. While holding the eraser end as still as possible, move the point in a circle to form a cone. The motion of the pencil is called *nutation.* The pencil point corresponds to the transmitting end of a waveguide feed.

The important point is that the polarization of the RF beam does not change during a nutation cycle. This means that the axis of the moving feed horn must not change horizontal or vertical orientation while the feed is moving. The movement might be compared to that of a Ferris wheel; the orientation of the seats remains vertical, regardless of where they are on the wheel.

Nutating Waveguide

The waveguide feed is a metal pipe, usually rectangular in cross section. The open end of the waveguide feed faces the antenna disk reflector, and the energy it emits is bounced from the reflector surface.

A conical scan can be generated by nutation of the waveguide feed. In this process, the axis of the waveguide feed is nutated through a narrow conical pattern.

This movement is fast (from 30 to 60 hertz) and small in amplitude. To an observer, the waveguide feed would appear to be vibrating slightly. The amplitude of the nutation determines the angle of the cone. The amplitude is kept small so that sufficient power is present in the center of the conical pattern for target tracking. Figure 2-5 shows the conical pattern produced by nutating the RF beam.

Angle Tracking

The radar's angle error-detecting circuits provide correction signals to the antenna and director drive circuits. The correction signals are proportional to the target displacement from the nutation axis of the antenna. Target displacement is detected by first locking onto the target in range, so that only that target is gated and used for angle tracking.

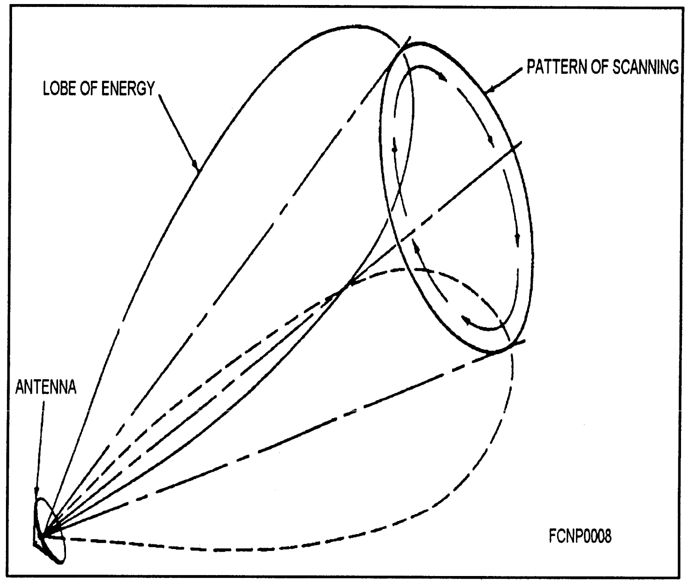

Figure 2-5.—Nutating lobe.

A two-phase reference generator in the antenna establishes the position of the feed horn relative to the nutation axis of the antenna. The generator provides the reference voltages for the angle error-detection circuits. The elevation reference voltage is 900 out of phase with the azimuth reference voltage.

Each error-detector circuit compares the phase of its reference voltage with the phase of its video envelope. The phase comparison indicates the direction of the error. The amplitude modulation of the video envelope is compared to the amplitude of the reference voltage to determine the amount of error.

ELECTRONIC SCANNING

Several techniques are used for electronic scanning. The two most common techniques used in fire-control radars are monopulse (simultaneous lobing) scanning and phasing scanning.

Monopulse scanning does not move the transmitted beam; instead, the echo signal is scanned or compared. Phasing scanning causes an actual movement of the radar beam with respect to the antenna axis. In addition, electronic scanning includes conical-scan-on-receive-only (COSRO) scanning techniques.

Monopulse Scanning

With monopulse (simultaneous lobing) scanning, range, bearing, and elevation angle information of a target is obtained from, as the name implies, a single pulse. This type of tracking radar normally produces a narrow circular beam of pulsed RF energy at a high pulse-repetition rate (PRR). Each pulse is divided into four signals that are equal in amplitude and phase. The four signals are radiated at the same time from each of four feed horns that are grouped in a cluster.

The radiated energy is focused into a beam by a microwave lens. In turn, energy reflected from the target is refocused by the lens into the feed horns. The amount of the total energy received by each horn varies, depending on the position of the target relative to the beam axis. The four targets are at different positions with respect to the beam axis. A phase inversion takes place at the microwave lens similar to the image inversion in an optical system.

The amplitude of returned signals received by each horn is continuously compared with those received in the other horns, and error signals are generated that indicate the relative position of the target with respect to the axis of the beam. Angle servo circuits receive these error signals and correct the position of the radar antenna and the director to keep the beam axis on target.

An important advantage of a monopulse-tracking radar over a radar using conical scan is that the instantaneous angular measurements are not subject to errors caused by target scintillation. Scintillation is the rapid fluctuation of the echo signal amplitude as the target maneuvers or moves, resulting in radar beams bouncing off different areas of the target and causing random reflectivity, which may lead to tracking errors. A monopulse-tracking radar is not subject to this error because each pulse provides an angular measurement without regard to the rest of the pulse train; therefore, scintillation does not affect the measurement.

An additional advantage of monopulse tracking is that no mechanical action is required, such as a scanner. Figure 2-6 (on page 2-8) shows monopulse variations of received energy with target positions.

Phasing Scanning

Phased array antennas use the phasing scanning method. This method controls the phase of the RF signals fed to multiple feed horns, dipoles, or radiators. The angular position of the beam is determined by the relative phase of the signals at each element. When the phase of the signals applied is changed, the beam can be steered without moving the antenna.

Another method of phasing uses changes in the transmitter frequency. Changing the frequency changes the wavelength; thus, with a fixed length of waveguide between the elements, the phase relationship changes as the frequency changes.

Phased arrays can be used for tracking by a monopulse-receiving technique. The array is divided into quadrants, with each quadrant equivalent to one of the four horns. The sum of all four quadrants is compared to the sums and differences of different quadrants, just as in monopulse scanning. This technique is also adaptable to receive-only antenna systems.

COSRO Scanning

Scanning the received signal by electronically switching between the antenna elements (feed horns) to produce a conical antenna receive pattern is called *conical-scan-on-receive-only* (COSRO). COSRO scanning is used with monopulse transmissions and with single-beam transmissions.

Angle errors are produced in much the same way as mechanical conical scanning. However, COSRO scanning is less effective than monopulse scanning, since many pulses are required to produce the target-echo envelope. While COSRO scanning is used more effectively with CW radars that use a separate receive antenna, it may also be used as an alternate tracking method, such as an electronic protection (EP) technique.

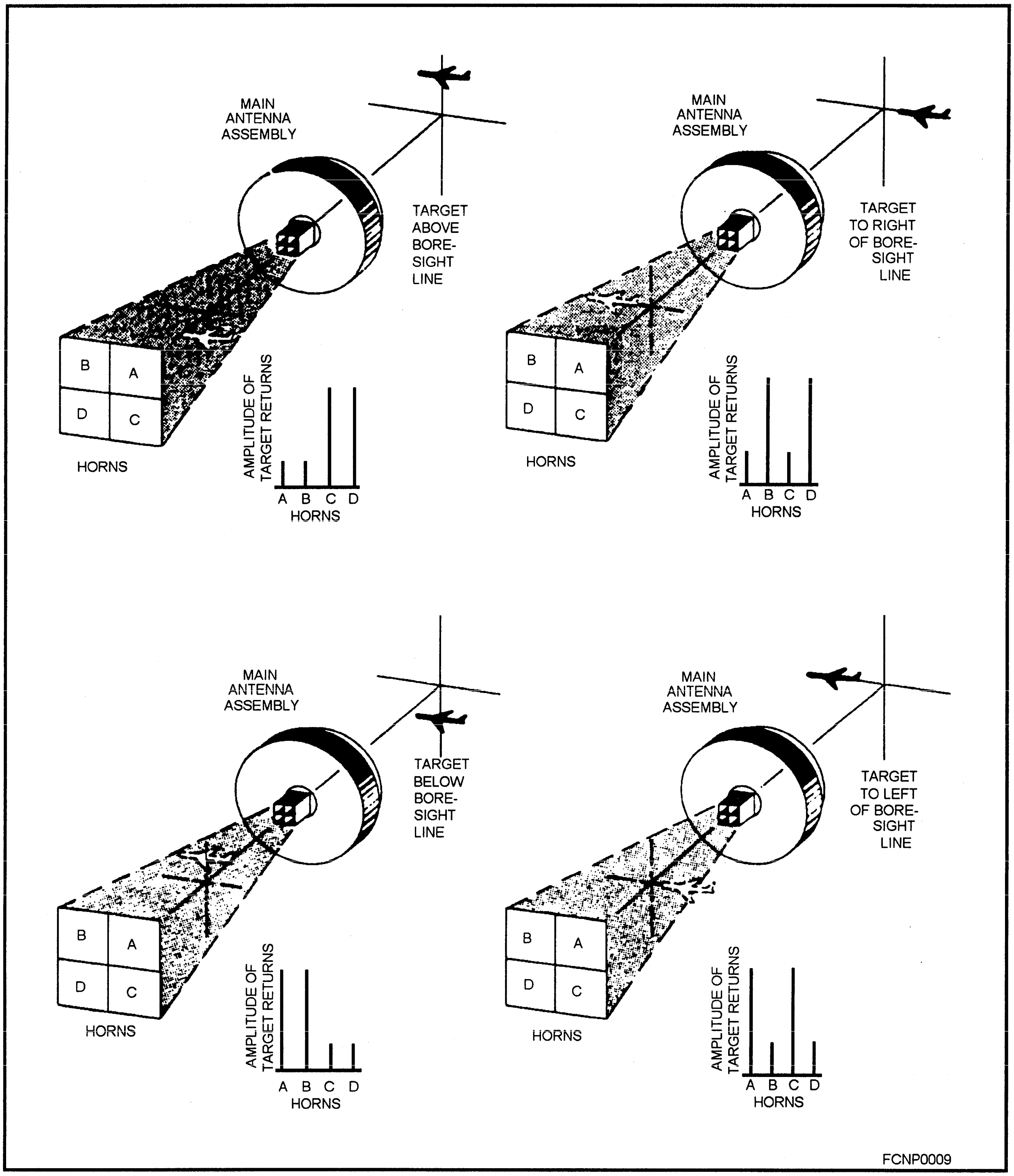

Figure 2-6.—Monopulse variations of received energy with target position.

TRANSMITTERS

Search and fire-control radars require high-powered oscillators and amplifiers to produce the transmitted RF signal. The high-power levels required for these radars enable the detection and tracking of targets at extended ranges. Solid-state transmitters have replaced most of the radar transmitters that once used vacuum tubes to provide high-power RF energy.

The high-power tubes used fall into two categories-crossed field and linear beam. Each type has different characteristics, making one tube more suited for one application than another.

CROSSED-FIELD TUBES

Crossed-field tubes get their name from the fact that the dc electric field and the magnetic field are crossed at right angles. One of the first crossed-field tubes used in early radars was the magnetron, and it was the only one available for quite a few years. Crossed-field tubes are also known as *M-type devices,* since they deal with propagation of waves in a magnetic field.

There are two types of crossed-field tubes: resonant and nonresonant.

- **Resonant Tubes:** Resonant tubes are oscillators and generate the RF signal. The most common resonant crossed-field tube used in radars is the magnetron.

- **Nonresonant Tubes:** Nonresonant crossed-field tubes are amplifiers and generally will not oscillate, but, instead, will amplify an applied RF signal. The amplifiers are subclasses as to whether they use the forward or backward wave and whether they are reentrant. *(Reentrant* means whether the electrons emitted by the cathode that return to the cathode can reenter the charge that travels to the anode or are then lost [wasted].) Only one type of nonresonant crossed-field tube has found wide use in radar application: the crossed-field amplifier (CFA). The CFA, discussed in a later subsection, is nonresonant, backward wave, and reentrant.

Magnetrons

Basically, the magnetron is a diode and has no grid. A magnetic field in the space between the plate (anode) and the cathode serves as a grid. The plate of a magnetron does not have the same physical appearance as the plate of an ordinary electron tube. Since conventional inductance-capacitance (LC) networks become impractical at microwave frequencies, the plate is fabricated into a cylindrical copper block containing resonant cavities that serve as tuned circuits.

The magnetron base differs greatly from the conventional base, as it has short, large-diameter leads that are carefully sealed into the tube and shielded. The cathode and filament structure is at the center of the tube and is supported by the filament leads, which are large and rigid enough to keep the structure fixed in position. The output lead is usually a probe or a loop extending into one of the tuned cavities and coupled into a waveguide or a coaxial line.

The plate structure is a solid block of copper. The cylindrical holes around its circumference are resonant cavities. A narrow slot runs from each cavity into the central portion of the tube and divides the inner structure into as many segments as there are cavities. Alternate segments are strapped together to put the cavities parallel to the output. These cavities control the output frequency. The straps are circular metal bands that are placed across the top of the block at the entrance slots to the cavities.

Since the cathode must operate at high power, it must be fairly large and be able to withstand high operating temperatures. It must also have good emission characteristics, particularly under back bombardment, because much of the output power is derived from the large number of electrons emitted when high-velocity electrons return to strike the cathode. The cathode is indirectly heated, and is constructed of a high-emission material. The open space between the plate and the cathode is the interaction space, where the electric and magnetic fields interact to exert force upon the electrons.

The magnetic field is usually provided by a strong, permanent magnet mounted around the magnetron so that the magnetic field is parallel with the axis of the cathode. The cathode is mounted in the center of the interaction space. The direction of an electric field is from the positive electrode to the negative electrode.

The law governing the motion of an electron in an electric (E) field states that the force exerted by an electric field on an electron is proportional to the strength of the field. Electrons tend to move from a point of negative potential toward a positive potential. In other words, electrons tend to move against the E field. When an electron is being accelerated by an E field, energy is taken from the field by the electrons.

The law of motion of an electron in a magnetic (H) field states that the force exerted on an electron in a magnetic field is at right angles to both the field and the path of the electron. The direction of the force is such that the electron trajectories are clockwise when viewed in the direction of the magnetic field.

Magnetron oscillators are divided into two classes: negative resistance and electron resonance.

- **Negative Resistance:** A negative resistance magnetron oscillator operates by a static negative resistance between its electrodes and has a frequency equal to the natural period of the tuned circuit connected to the tube. The split-anode negative resistance magnetron is a variation of the basic magnetron, which operates at a higher frequency and is capable of more output.

- **Electron Resonance:** An electron resonance magnetron oscillator operates by the electron transit-time characteristics of an electron tube (the time it takes electrons to travel from the cathode to the plate). It is capable of generating very large peak-power outputs at frequencies in the thousands of megahertz. The electron resonance magnetron is most widely used for microwave frequencies. Modern designs have a reasonably high efficiency and relatively high output. However, one disadvantage of the electron resonance magnetron is that its average power is limited by the cathode emission. Furthermore, the peak power is limited by the maximum voltage that it can withstand without damage.

The operation, coupling methods, tuning, and seasoning of magnetrons are discussed in the following subsections. Since this information is general in nature, the recommended times and PMS procedures in equipment technical manuals should be followed when baking-in a specific type of magnetron. Figure 2-7 shows a magnetron.

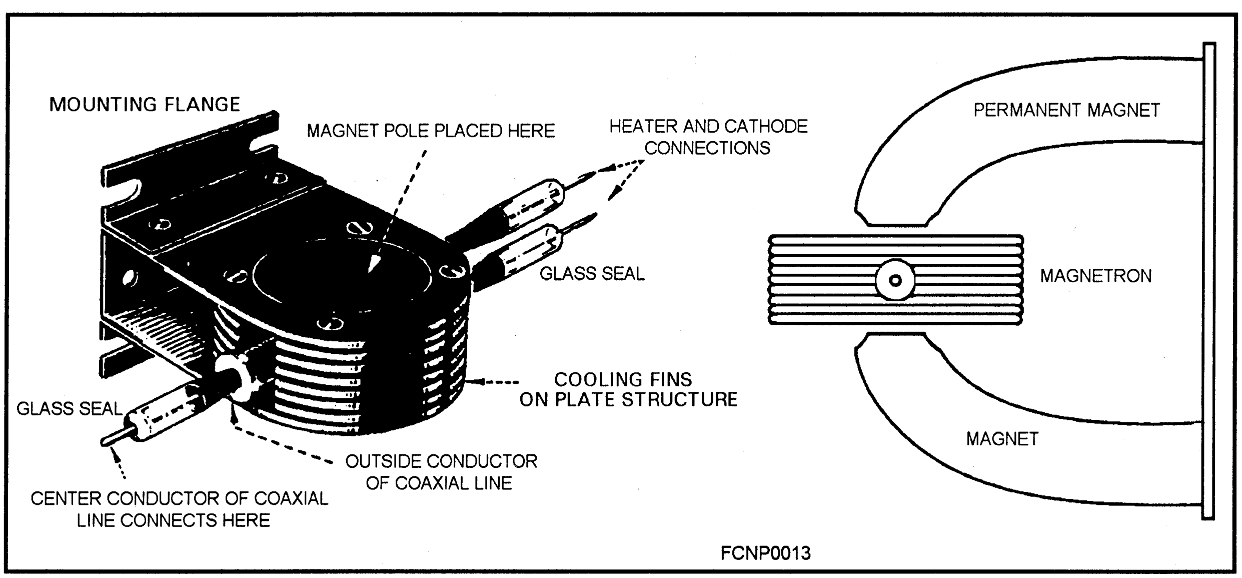

Figure 2-7.—Magnetron.

MAGNETRON OPERATION.— The electric field in the electron resonant oscillator consists of the alternating current (at) and direct current (de) fields. The action of electronics taking energy away from the ac fields is an undesirable effect. The dc field extends radially between adjacent anode segments by the RF oscillations induced in the cavity tank circuits of the anode block. For more information on magnetron operation, refer to your appropriate operating procedures for your fire-control system.

MAGNETRON COUPLING METHODS.— The RF energy can be removed from a magnetron by a coupling loop. At frequencies lower than 10,000 MHz, the coupling loop is made by bending the inner conductor of a coaxial cable into a loop and soldering the end to the outer conductor so that the loop projects into the cavity. To obtain sufficient pickup at higher frequencies, the loop is located at the end of the cavity.

MAGNETRON TUNING.— A tunable magnetron permits the system to be operated at a precise frequency anywhere within a band of frequencies, as determined by the magnetron's characteristics. The resonant frequency of a magnetron can be varied by varying the inductance or capacitance of the resonant cavities.

MAGNETRON SEASONING.— During initial operation, a high-power magnetron arcs from the cathode to the plate and must be properly broken-in or baked-in. Actually, arcing in magnetrons is very common. It may occur with a new tube or following a long period of idleness.

One of the prime causes of arcing is the liberation of gas from tube elements during idle periods. Arcing may also be caused by sharp surfaces within the tube, mode shifting, and excessive current. Although the cathode can withstand considerable arcing for short periods of time, continued arcing will shorten the life of the magnetron and may destroy it entirely. Hence, each time excessive arcing occurs, the tube must be baked-in again until the arcing ceases and the tube is stabilized.

The baking-in procedure is relatively simple. Magnetron voltage is raised from a low value until arcing occurs several times a second. The voltage is left at that value until arcing dies out. Then the voltage is raised further until arcing again occurs, and it is left at that value until the arcing again dies out. Whenever the arcing becomes very violent and resembles a continuous arc, the applied voltage is excessive and should be reduced to permit the magnetron to recover. When the normal rated voltage is reached and the magnetron remains stable at the rated current, the baking-in is complete. It is a good maintenance practice to bake-in magnetrons left idle in the equipment, or those used as spares, when long periods of non-operating time have accumulated.

Crossed-Field Amplifier

The crossed-field amplifier (CFA) is constructed very similar to a magnetron. The major difference is that the CFA requires an RF input in addition to the electrical input and the magnetic field.

The CFA anode is very similar to that of a regular trapezoid block magnetron, with the exception of the drift tube section. The drift tube section serves two purposes: (1) to dampen out electron bunches, and thus oscillations, as the spokes move past the output port, and (2) to provide a path for RF energy from the input to the output.

The CFA is normally used in a chain of two or more CFAs in series. When the CFA is not pulsed with high voltage, the tube presents a low-impedance-to-input RF and passes it through to the output port. When used in a chain, one or more CFAs can be energized, depending on the output power required. For example, for close-in targets, the final stage or stages may not be needed, but all CFAs are required for detecting small targets at maximum range.

The cathode of a CFA is cylindrical, just as in magnetrons; however, most are *cold* cathodes (no filaments or heaters). With a cold cathode, sufficient electron emission is available to form a space charge when an electric field is applied. The electrons will not achieve sufficient velocity to escape the region close to the cathode without an RF field applied. Initially, when an RF field is applied, the electrons gain some energy from the RF and move farther out from the cathode. While some will gain even more energy and reach the anode, others will return to the cathode and strike with sufficient energy to cause secondary emission and increase the electrons in the space charge. Therefore, the major source of electrons is secondary emission from the reentrant electrons.

Secondary emission generates heat in the cathode and further increases emission. If the cathode becomes too hot, thermionic emission may become sufficient to allow the tube to oscillate or to produce noise, even though an RF field has not been applied. To prevent the spurious generation of noise, the cathode is usually water-cooled. Another means of reducing noise output is to make the RF pulse slightly wider than the high-voltage pulse.

Further control is found on some tubes with a bias electrode (a cutoff electrode). The bias electrode has a positive pulse (with respect to the cathode) applied just before the end of the RF pulse. The cutoff pulse allows the electrode to collect the electrons in the drift-tube region and the tube to shut off. The pulse must be wide enough to extend past the end of the RF pulse.

CFAs do not have the gain of some of the linear-beam tubes. However, they do have three advantages.

1. The CFAs, when used in a multistage chain, can produce equal or greater overall gain at lower high-voltage requirements than a linear- beam amplifier, such as a multicavity klystron. For example, a typical CFA can deliver a 1-megawatt RF peak power output with a 40-kilovolt, 50-ampere peak pulse, where a klystron would require a 90-kilovolt, 40-ampere peak pulse to produce the same RF output. However, the CFA would require a higher power level input drive signal than the klystron.

2. The CFA is a cold cathode, which normally has a much longer operating life than a heated cathode.

3. The CFA produces far less X-rays than linear-beam tubes; therefore, lead shielding is not required.

LINEAR-BEAM TUBES

A linear-beam tube uses a magnetic field that is parallel to the electron beam and is used to focus the beam. Some tubes do not use a magnetic field; instead, electrostatic focusing is used to hold the beam together while it travels the length of the tube. The two most common types of linear-beam tubes used in fire-control equipment are the klystron amplifier and the traveling-wave tube.

Klystron Amplifiers

The basic theory of a klystron amplifier is quite simple. The klystron amplification principle may be readily explained with an analogy to a simple triode amplifier with tuned plate and grid circuits. Klystron amplifiers include two-cavity power klystrons and multicavity power klystrons.

TWO-CAVITY POWER KLYSTRON AMPLIFIERS.— Figure 2-8 shows a simplified schematic of a triode amplifier with resonant circuits at both the input and the output. Such resonant circuits restrict the bandwidth of the amplifier and increase the gain.

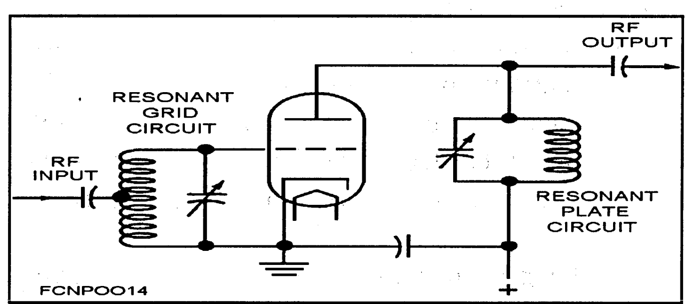

Figure 2-8.—Simplified schematic of a triode amplifier with resonant circuits at both the input and the output.

A triode tube consists of three elements: (1) a cathode that emits a stream of electrons, (2) a grid that controls the electron stream, and (3) a plate that attracts the electrons and catches them after they pass through the grid.

1. **Cathode:** The cathode emits a stream of electrons.

2. **Grid:** The grid acts as a valve, opening or closing the current path according to the voltage applied to it. The RF input signal comes to the grid as a weak alternating voltage. This voltage modulates the electron flow through the tube at the radio frequency.

3. **Plate:** The electron stream then delivers, at the plate, an alternating current, which is an amplified reproduction of the input signal. This alternating current flows through the resonant plate circuit and excites alternating voltages across it. These voltages constitute the RF output from the amplifier.

The time it takes electrons to cross the tube is approximately one-billionth of a “second. This transit time is short compared to the period of a cycle of a radio wave below the microwave range (approximately one-millionth of a second). Hence, the electrons are slowed down or speeded up by the voltage on the grid at a given instant. The flow of electrons, therefore, can follow the voltage fluctuation on the grid.

In the case of microwaves, however, the oscillations are so rapid (the cycle period is so short) that the voltage on the grid may go through several complete oscillations while a particular quantity of electrons travel across the tube. In other words, the grid voltage changes too rapidly for the electrons to follow the fluctuation. There are other reasons why the conventional triode tube fails at microwave frequencies, but the most fundamental reason is that the transit time of the electrons is long when compared to the period of one cycle of the microwave signal.

The klystron amplifier makes a virtue of the very thing that defeats the triode—the transit time of the electrons. The klystron amplifier modulates the velocity of the electrons, so that as the electrons travel through the tube, electron bunches are formed. These bunches deliver an oscillating current to the output resonant circuit of the klystron. The klystron amplifier consists of three separate sections: the electron gun, the RF section, and the collector.

- **Electron Gun:** The electron gun consists of a heater, a cathode, a control grid, and an anode. Electrons are emitted by the cathode and drawn toward the anode, which is operated at a positive potential with respect to the cathode. The electrons are formed into a narrow beam by either electrostatic or magnetic focusing techniques. The control grid is used to control the number of electrons that reach the anode region. It may also be used to turn the tube completely on or off in certain pulsed-amplifier applications. Well-formed by the time it reaches the anode, the electron beam passes through a hole in the anode and on to the RF section of the tube, eventually striking the collector. The electrons are returned to the cathode through an external power supply. It is evident that the collector of a klystron amplifier acts much like the plate of a triode insofar as the collecting of electrons is concerned. However, there is one important difference. The plate of a triode is normally connected, in some fashion, to the output RF circuit, whereas in a klystron amplifier, the collector has no connection to the RF circuitry at all.

- RF Section: The RF section of a basic klystron amplifier is quite different from a conventional triode amplifier. The resonant circuits used in a klystron amplifier are reentrant cavities.

- Collector: The collector is normally insulated from the RF section of large klystron amplifiers to permit separate metering of the electrons intercepted by the drift tubes and those intercepted by the collector. The electrons intercepted by the RF section are called *body current*, whereas electrons intercepted by the collector are referred to as *collector current.* Obviously, the sum of the body current and the collector current is equal to the total current in the electron beam, which is called *beam current*. Klystron amplifier specifications often place a maximum limit on allowable body current. The collector of most high-power klystrons is insulated from the body of the tube, This allows separate metering and overload protection for the body current and the collector current. In most systems, the collector and the body operate at nearly the same potential. Any potential difference is usually only the difference in voltage drop across the various metering circuits.

MULTICAVITY POWER KLYSTRON AMPLIFIERS.— The simple, two-cavity power klystron amplifier is not capable of high-gain or high-power output, or suitable efficiency. However, with the addition of intermediate cavities and other physical modifications, the basic two-cavity klystron may be converted into a multicavity power klystron, capable of both high-gain and high-power output.

In addition to the intermediate cavities, there are several physical differences between the basic two-cavity klystron and the multicavity klystron. The cathode of the multicavity power klystron must be larger to be capable of emitting large numbers of electrons. The shape of the cathode is usually concave, which aids in focusing the electron beam. The collector must also be larger to allow for greater heat dissipation. In a high-power klystron, the electron beam may strike the collector with sufficient energy to cause the emission of X-rays from the collector. Many klystrons have a lead shield around the collector as protection against X-rays. Most high-power klystrons are liquid-cooled and must be constructed to facilitate cooling the collector.

Klystron amplifies have as many as seven cavities, including five intermediate cavities. The intermediate cavities improve the bunching process, resulting in increased efficiency. Adding more intermediate cavities is roughly analogous to adding more stages to an IF amplifier; that is, the overall amplifier gain is increased and the overall bandwidth is reduced—if all the stages are tuned to the same frequency.

The same effect occurs with klystron amplifier tuning. A given klystron amplifier tube will deliver high gain and narrow bandwidth if all the cavities are tuned to the same frequency-this is called *synchronous tuning.* If the cavities are tuned to slightly different frequencies, the gain of the klystron amplifier will be reduced and the bandwidth may be appreciably increased—this is called *asynchronous tuning.* Most klystron amplifiers that feature relatively wide bandwidths are stagger-tuned.

The klystron is not a perfectly linear amplifier; that is, the RF power output is not linearly related to the RF power input at all operating levels. In other words, the klystron amplifier will saturate, just as a triode amplifier will limit if the input signal becomes too large. In fact, if the RF input is increased to levels above saturation, the RF power output will actually decrease.

To better understand the reason for this decrease, remember that electron bunches are formed by the action of the RF voltage across the input cavity gap. This RF voltage accelerates some electrons and slows down other electrons, resulting in the formation of bunches in the drift tube region. Obviously, this speeding up and slowing down effect is increased as the RF drive power is increased.

The saturation point is reached when the bunches are perfectly formed at the instant they reach the output cavity gap. This results in the maximum power output condition. When the RF input is increased beyond this point, the bunches are perfectly formed before they reach the output gap; that is, they form too soon. By the time the bunches have reached the output gap, they tend to debunch because of the mutual repulsion of electrons and because the faster electrons have overtaken and passed the slower electrons. This causes the output power to decrease.

FOCUSING KLYSTRON AMPLIFIERS.— One very important item that is required for high-power klystron amplifier operation is an axial magnetic field (a magnetic field parallel to the axis of the klystron). In klystron amplifiers, which are physically long, it is difficult to keep the electron beam properly formed during its travel through the RF section. The mutual repulsion between electrons causes the beam to spread in a direction perpendicular to the axis of the tube. If this is allowed to occur, electrons will strike the drift tube and be collected there, rather than passing through the drift tube to the collector.

To overcome beam spreading, an axial magnetic field is used. The action of the magnetic field is to exert a force on the electrons that keeps them focused into a narrow beam. The magnetic field may be developed by a permanent magnet or by one or more electromagnets. A permanent magnet is used in tubes that are physically small or of medium power rating. Unfortunately, the size and the weight of a permanent magnet are excessive for long or high-power tubes, making it necessary to use electromagnets. In some large tubes, several separate electromagnets are used. The current in each coil is individually adjustable to optimize the magnetic field shape. The magnetic field is normally terminated a short distance beyond the output cavity so that the beam can spread before it hits the collector. This tends to spread the electron beam interception over a large surface on the collector, minimizing collector cooling problems that otherwise would result from the beam remaining concentrated at the time of interception.

Even with an axial magnetic field, some electrons stray from the main electron beam. These electrons are intercepted by the anode or the klystron drift tubes. In high-power tubes, it is particularly important to minimize the number of stray electrons because of the heat generated when they strike the drift tubes. And in a high-power klystron, this heating maybe a very severe problem because drift tubes are quite difficult to cool. Temperatures may become high enough to melt the drift tubes, thus destroying them.

Klystron amplifiers normally have actual metal grid structures across the gaps in the resonant cavities. Many low-power klystrons have wire mesh grids. However, most high-power klystrons do not have actual grids across the gaps. Such grids would intercept sizable quantities of electrons.

It is very difficult to cool grid structures, and a large amount of beam interception would melt the grids, thus destroying the tube. Fortunately, by proper design, the klystron may be made to operate efficiently without actual grid wires across the cavity gaps. The absence of these grids does not change the operating principles, but it does have a secondary effect on klystron performance. If the electron beam has a small diameter compared to the diameter of the drift tube, the beam does not couple energy to the cavities very well. Therefore, the performance of a klystron amplifier, which does not have gridded gaps, may sometimes be improved by permitting the electron beam to be as wide as possible, while keeping the body current down to the maximum specified for the tube. The width of the beam may be somewhat controlled by the magnetic field strength.

Body current usually increases with RF input level, because it is the RF input that causes the bunches to form. The dense electron concentration in the bunch causes mutual repulsion of electrons, and the diameter of the bunch may become larger than the diameter of the beam with no bunches present. Consequently, some of the electrons in the bunch may be lost to the drift tubes, and the body current may increase.

ADDITIONAL EQUIPMENT FOR KLYSTRON AMPLIFIERS.— Additional equipment is required for a complete amplifier system. Various power supplies are necessary to deliver required voltages and current. In high-power systems, various RF circuit components are required to control and measure the RF input to the klystron tube and to measure the RF output from the tube. A large collection of meters and protective devices is needed to monitor performance and protect operating personnel and equipment in the event of a malfunction or operator error.

In most klystron tubes, the anode and the RF section are connected inside the vacuum envelope. These connected parts are called the *tube body* and are generally operated at ground potential. It is convenient to operate the tube body at ground potential because the input and output connections (either waveguide or coaxial) are then also at ground potential. This makes it easier to connect the klystron into the rest of the system. In addition, the cavity tuners are at ground potential, eliminating any danger to personnel tuning the tube.

The beam supply provides the voltage required to accelerate the electrons and form the beam. It must also deliver the required beam current. The crowbar system quickly discharges the beam supply in the event of an internal klystron arc or other high-voltage fault condition. For high-power systems, it is normal to have some value of series resistance between the beam supply and the klystron cathode. This limits tube current to a finite value if the tube should arc from cathode to ground.

Some klystrons have a grid or a modulating anode to control the number of electrons in the electron beam. Such grids are often used in pulse systems to turn the tube full-on or full-off. A few systems use grid modulation to transmit intelligence.

In most gridded klystron tubes, the grid is never allowed to go positive with respect to the cathode, as it might cause undue grid interception of the beam and result in the burnout of the grid element. A grid power supply is required in those tubes that have grids. These power supplies and pulsers may take many forms, depending on the system application, and, therefore, are not discussed in this chapter.

Some klystrons are made with the electromagnets physically part of the tube itself. However, in most systems, the electromagnets are separate from the tube, and the klystron is inserted into the electromagnet structure.

Many modern klystrons have only one electromagnet, and, therefore, require only one power supply. Others may have as many as six separate coils, requiring one power supply for each coil. Voltage and current metering is usually supplied for each of the electromagnet power supplies.

If an electromagnet power supply should fail, the electron beam would almost certainly spread, and most of the beam current would be intercepted on a small section of the drift tube. In most cases, this would cause the drift tube to melt and permanently destroy the tube. Therefore, klystron amplifier equipment normally has undercurrent protection in each of the electromagnet circuits.

When the electromagnet current falls below a predetermined level, the beam supply is automatically turned off to prevent damage to the klystron. Redundant protection is provided by the body-current overload circuits, which also turn off the beam supply in the event of magnet current failure or misadjustment.

Figure 2-9 (on page 17) is a simplified diagram showing some of the power supplies, monitoring devices, and protective devices used in a typical power klystron amplifier. It also shows three electromagnets wrapped around the body of the klystron. In addition, figure 2-9 shows a method used to monitor body current, collector current, and beam current separately. (In many systems, separate monitoring of collector current is not done, since the collector current and the total beam current are almost equal.)

It is quite unusual in a relatively high-power klystron amplifier system to allow the body current to exceed 10 percent of the beam current. High body current usually means low efficiency, and it increases the danger of burning out drift tubes. In very-high-power klystrons, the body current is often limited from 1 to 2 percent of the total beam current.

If a klystron arcs internally, the arc will always occur between the cathode and the anode. When this occurs, the body current immediately becomes excessive, tripping out the body-current overload relay. An arc also causes beam current to be much higher than normal, and the beam-current overload will also trip out. In fact, almost any high-voltage system fault (such as an insulation breakdown) will cause excessive current through the body-current meter and the overload relay.

Because of the possibility of extremely high currents flowing under fault conditions, the protection of body-current and beam-current meters presents a somewhat difficult problem. This problem is usually solved by using very-high-current, solid-state rectifiers, back to back, across the meters.

In some cases, it is necessary to add a small resistance or inductance in series with the meter. Surge capacitors are normally placed across the combination. It is necessary to connect the rectifiers back to back because fault conditions often cause oscillating currents to flow through the meters.

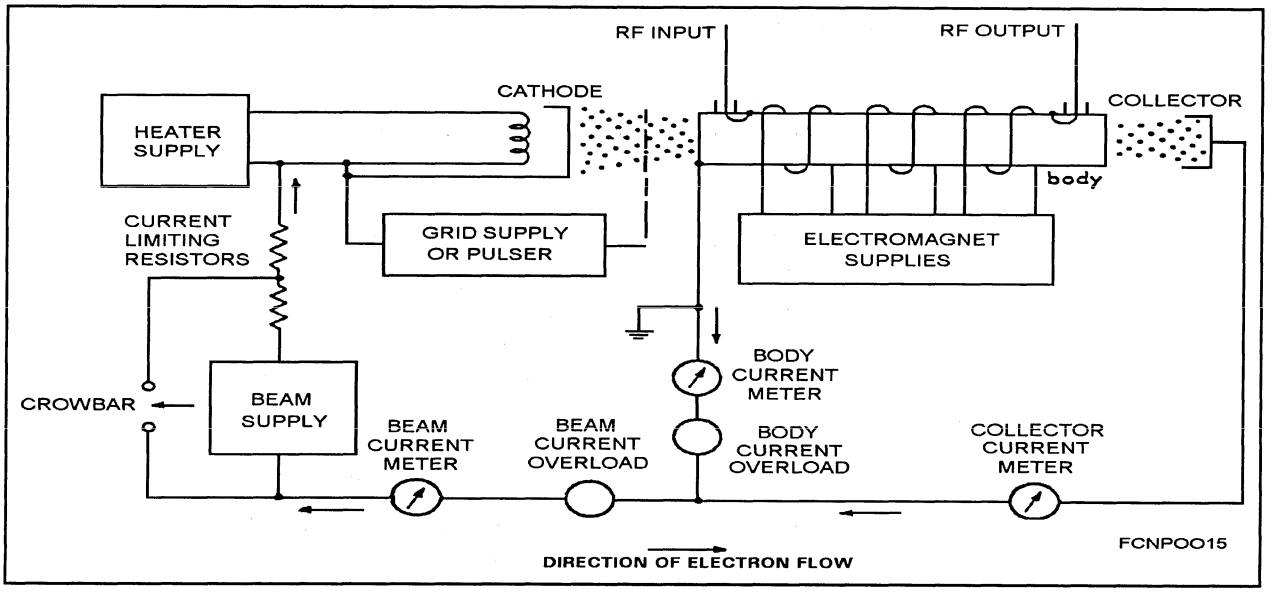

Figure 2-9.—Associated klystron amplifier equipment.

COOLING KLYSTRON AMPLIFIERS.— Most low-power klystron amplifiers are air-cooled, whereas all high-power klystrons are liquid-cooled. It should be stressed that the technician responsible for maintaining the klystron transmitter must be familiar with the cooling system of the equipment. It should also be stressed that an expensive klystron amplifier system may be destroyed in a matter of seconds if the cooling system fails. A well-designed system uses many protective devices to prevent this from happening.

The main source of power and heat in a klystron amplifier package is the beam power supply. Since the power generated by the beam supply must go somewhere, part of it is converted to RF power, while the remainder eventually shows up as heat somewhere in the klystron. Klystron cooling is required to be able to dissipate the entire beam power. This is necessary, because if no RF output is being generated (either due to low RF input power or detuning of the klystron tube), all the beam power will be dissipated as heat somewhere within the tube. When most of the electrons in the beam eventually strike the collector, their energy is dissipated as heat. Also, the small fraction of the beam lost to the drift tube generates heat.

Klystron amplifiers are normally from 30 to 50 percent efficient. Therefore, a tube rated at 10-kilowatt output must be designed to dissipate between 10 and 23 kilowatts, depending on its efficiency. A tube rated at 100 kilowatts must be capable of dissipating between 100 and 230 kilowatts, depending on efficiency. Very advanced cooling techniques are necessary. The power levels involved may melt a hole in the drift tube or the collector in a small fraction of a second if the cooling system fails and adequate protective devices are not provided.

There are other, smaller sources of heat in a klystron amplifier system. The heat produced by the heater is conducted and radiated to the exterior surfaces of the electron gun assembly and must be dissipated. Large tubes require a blower on the electron gun assembly to dissipate this heat. The power generated by the focus coil power supply is all dissipated in the electromagnets. Large electromagnets are usually liquid cooled. If the electromagnet cooling fails for any reason, the focus coil power supply must be shut off very quickly, or the magnet will burn out. The beam voltage must also be removed (preferably before turning off the focus coil supply) to protect the tube from excessive body current.

During operation, the walls of the resonant cavities have oscillating currents flowing in them. Although these cavities are made of very high conductivity metal, they still present a finite resistance to these oscillating currents. Therefore, heat is generated in the cavity walls. The amount of heat generated may be quite sizable in high-power, high-frequency tubes.

For example, in a 20-kilowatt, 10-GHz klystron amplifier, approximately 1 kilowatt of heat is generated by the circulating RF currents in the output cavity. Since the cavity is approximately a 1-inch cube, it is apparent that removing the heat is a formidable problem.

Another problem associated with cavity heating is not immediately apparent. The resonant frequency of a cavity depends on its physical size. The cavities are made of metal, which expands as its temperature increases. This effect tends to change the resonant frequency of the cavities and, thereby, detune the tube. As the tube detunes, the power output drops. This, in turn, reduces the RF heating and allows the tube to come back into tune. If this problem were not considered in the initial tube design, the resulting tube would be unstable in its operation. This situation exists in some tubes that are external cavities. These external cavities are cooled by air, rather than by liquid, and the cavity tuning is seriously affected by the ambient air temperature.

All high-power klystrons are liquid-cooled, including cavities and tuners. The cavities are maintained at a stable temperature by controlling the temperature of the cooling liquid; therefore, thermal detuning is no longer a problem.

Drift-tube heating is a serious problem in very-high-power and medium-power, high-frequency klystrons. The drift tubes, which are inside the vacuum envelope, are physically small, and it is difficult to conduct the drift-tube heat into the region outside the vacuum envelope. In some high-power tubes, it is necessary to bring the cooling liquid inside the vacuum envelope and around the drift tubes to remove the heat.

In some high-power, high-frequency systems, it is necessary to cool the output waveguide. A 10-GHz waveguide carrying a 5-kilowatt signal becomes too hot to-touch in normal ambient air. Fortunately, waveguides may be cooled easily by soldering copper tubing along the sides of the guide and running cooling liquid through the tubing.

Systems that use blowers for cooling usually have an airflow switch; if the blower fails, the switch opens and removes power from appropriate power supplies. Systems that use liquid cooling normally distribute the liquid into a large number of paths, since the flow requirements are quite dissimilar. Each path has a low-flow interlock. If one of the liquid cooling circuits becomes plugged, the low-flow interlock opens and removes power from the system.

Distilled water is the best medium for cooling klystron amplifiers. Some very-high-power amplifiers specify that only distilled water may be used. Unfortunately, water freezes at a temperature that could be encountered under normal operating conditions. Many low- and medium-power klystrons permit the use of ethylene glycol and water as the cooling liquid.

However, since ethylene glycol reacts with certain types of metals and hoses that might be used in the system, special care must be taken in working on a system that uses ethylene glycol. Only nonferrous metals should be used in a cooling system for a klystron amplifier.

NOISE IN KLYSTRON AMPLIFIERS.— Volumes have been written about noise in microwave systems. However, this chapter covers only the high points. The output of a klystron amplifier contains harmonics primarily because the output cavity is excited by bunches of electrons that pass through the output gap once every cycle. Since the driving energy supplied to the output cavity is not continuous, but occurs in quick pulses, it is evident that the output current may not be purely sinusoidal. Therefore, the output contains harmonic components.

In general, the harmonic output of a klystron amplifier is largest when the tube is operated at or above saturation. Harmonic content decreases when the tube is operated below saturation. Also, harmonics in the output may be reduced by the use of harmonic filters.

Another source of distortion is the nonlinearity of the klystron. If the RF signal is amplitude modulated, the RF output may not perfectly follow the RF input, possibly resulting in the distortion increasing as the tube is driven closer to saturation on the peaks of the RF input signal. In general, klystron amplifiers should not be used to amplify amplitude-modulated signals if the RF output is driven higher than 70 percent of the saturation level. Considerable distortion may occur between 70 and 100 percent of saturation.

A klystron amplifier generates a certain amount of white noise, just as in any other electron tube. White noise occurs usually because an electron beam is never perfectly homogeneous. The amount of electrons varies slightly with time, primarily due to shot noise at the cathode surface. This variation shows up as random noise in the RF output. A certain amount of noise may also be generated by electrons striking the drift tubes.

Since klystron amplifiers are noisy, they are not usually used to amplify weak microwave signals, such as in a radar receiver RF amplifier.

Traveling-Wave Tubes

Traveling-wave tubes (TWTs) are high-gain, low-noise, wide-bandwidth microwave amplifiers, capable of gains of 40 dB or more, with bandwidths of over an octave. (A bandwidth of 1 octave is one in which the upper frequency is twice the lower frequency.) TWTs have been designed for frequencies as low as 300 MHz and as high as 50 GHz. The primary use for TWTs is voltage amplification (although high-power TWTs, with characteristics similar to those of a power klystron, have been developed). Their wide bandwidth and low-noise characteristics make them ideal for use as RF amplifiers.

TWT OPERATION.— While the electron beam in a klystron travels primarily in regions free of RF electric fields, the beam in a TWT is continually interacting with an RF electric field propagating along an external circuit surrounding the beam. To obtain amplification, the TWT must propagate a wave whose phase velocity is nearly synchronous with the dc velocity of the electron beam. It is difficult to accelerate the beam to greater than approximately one-fifth the velocity of light. Therefore, the forward velocity of the RF field propagating along the helix must be reduced to nearly that of the beam.

The phase velocity in a waveguide, which is uniform in the direction of propagation, is always greater than the velocity of light. However, this velocity can be reduced below the velocity of light by introducing a periodic variation of the circuit in the direction of propagation. The simplest form of variation is obtained by wrapping the circuit in the form of a helix, whose pitch is equal to the desired slowing factor.

TWT MIXER.— A TWT is also used as a microwave mixer. By virtue of its wide bandwidth, the TWT can accommodate the frequencies generated by the heterodyning process (provided that the frequencies have been chosen to be within the range of the tube). The desired frequency is selected by the use of a filter on the output of the helix. A TWT mixer has the added advantage of providing gain as well as simply acting as a mixer.

TWT MODULATION.— A TWT can be modulated by applying the modulating signal to a modulator grid. The modulator grid can be used to turn the electron beam on and off, as in pulsed microwave applications, or to control the density of the beam and its ability to transfer energy to the traveling wave. Thus, the grid can be used to amplitude modulate the output .

TWT OSCILLATOR.— A forward-wave TWT can be constructed to serve as a microwave oscillator. Physically, a TWT amplifier and an oscillator differ in two major ways. The helix of the oscillator is longer than that of the amplifier, and there is no input connection to the oscillator. TWT oscillators are often called *backward-wave oscillators* (BWOs) or carcinotrons.

The operating frequency of a TWT oscillator is determined by the pitch of the tube's helix. The oscillator can be tuned, within limits, by adjusting the operating potentials of the tube.

The electron beam passing through the helix induces an electromagnetic field in the helix. Although initially weak, this field will cause bunching of succeeding portions of the electron beam.

With the proper potentials applied, the bunches of electrons reinforce the signal on the helix. This, in turn, increases the bunching of succeeding portions of the electron beam. The signal on the helix is sustained and amplified by this positive feedback, resulting from the exchange of energy between the electron beam and the helix.

MODULATORS

Transmitter tubes all have one common requirement—a source of high voltage—whether they are operated in a CW or pulsed mode. A fixed high-voltage supply for CW operation is relatively simple compared to a pulsed high-voltage supply. A pulsed high-voltage power supply is called a *modulator,* which means to shape, as well as to control. Modulators are also called *pulsers* or *keyers,* depending on their circuit function.

The power supply provides the source of high voltage to charge the storage device. The storage device can be capacitive or inductive, or a combination of capacitance and inductance that stores electrical energy in the form of an electrostatic or electromagnetic field. Electrostatic storage is the most common method used.

The storage device is charged through the relatively high impedance of the charge path while the switch is open. The load is the high-power tube, which is usually connected by a step-up pulse transformer. The pulse transformer allows the dc to charge the storage device.

When the switch is closed, a low-impedance discharge path is provided for the storage device through the pulse transformer. The charge time is long compared to the discharge time because of the differences in impedances. The switch is normally an electronic element, such as a thyratron or a silicon-controlled rectifier (SCR), since mechanical switching is impractical at the pulse-repetition frequencies used in most radars.

There are many different types of pulse modulators in use today. The most common type found in fire-control applications is the line modulator. The basic elements of a line modulator are shown in figure 2-10.

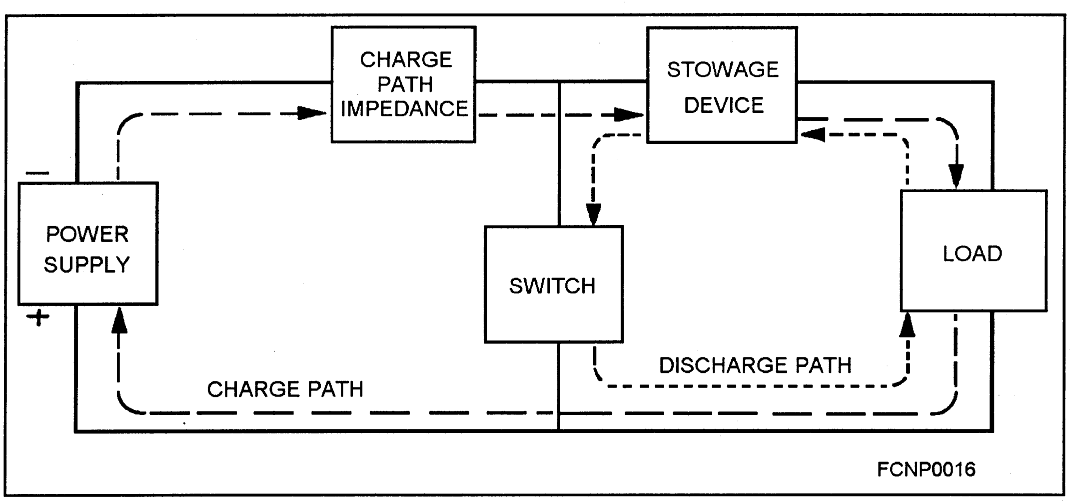

Figure 2-10.—Basic elements of a modulator.

RECEIVERS

The RF echo pulses reflected by a distant object are similar to the transmitted pulses, but they are considerably diminished in amplitude. These minute signals are amplified and converted into video pulses by the receiver. A voltage amplification of 10/10th is required to produce a video pulse of sufficient amplitude to intensify the beam of a CRT. The receiver must accomplish this amplification with a minimum introduction of noise voltages.

In addition to having a high-gain and low-noise figure, the receiver must provide a sufficient bandwidth to pass the many harmonics contained in the video pulses to minimize distortion of the pulses. The receiver must also accurately track the transmitter in frequency, since drift diminishes the reception of the echo signal. The receiver tuning range need only be equal to that of the transmitter.

This section discusses receiver system functional areas and radar displays.

RECEIVER SYSTEM FUNCTIONAL AREAS

As you study this section, refer to figure 2-11 (on page 22), which is a simple block diagram of radar receiver general functions based on the superheterodyne principle. The superheterodyne receiver is used exclusively in radar systems.

The echo signal enters the system through the antenna. It then passes through the duplexer and is amplified by the low-noise amplifier (LNA). (TWTs, parametric amplifiers, and masers are representative devices that are used as low-noise, high-gain RF amplifiers.) When external noise is negligible, the noise generated by the input stage of the receiver largely determines the receiver sensitivity.

In many receivers, an LNA is not used and the mixer is the first stage (as indicated by the dashed path in figure 2-11). The function of the mixer stage, or the first detector, is to translate the RF to a lower intermediate frequency—usually 30 or 60 MHz—by heterodyning the returning RF signal echo with a local oscillator signal in a nonlinear device (mixer) and extracting the signal component at the difference frequency. By using the IF, the necessary gain is easier to obtain than by using the higher RF. It is also easier to develop the response function (or bandpass characteristic) of the receiver IF stages.

One of the requirements of the radar receiver is that its internal noise be kept to a minimum. It is important, therefore, that the input stages of receivers be designed with low-noise figures. If the mixer is the first stage, its crystal characteristics will include low conversion loss and a low-noise-to-temperature-change ratio. Any noise generated by the local oscillator must be kept out of the mixer stage, either by the insertion of a narrowband filter between the local oscillator and the crystal, or by a balanced mixer.

Since the bandwidth of the RF portion of the receiver is relatively wide, the frequency-response characteristic of the IF amplifier determines the overall response characteristic of the receiver. It is in the design of the IF portion of the receiver that the response characteristics are accomplished, in the same manner that the signal-to-noise ratio is accomplished.

The receiver system fictional areas discussed in this section include the automatic frequency control system, local oscillators, frequency synthesizers, radar receiver mixers, IF amplifiers, gain controls, logarithmic IF amplifiers, detectors, and pulse compressions.

Automatic Frequency Control System

The automatic frequency control (AFC) system normally used to keep the receiver in tune with the transmitter is called the *difference frequency system.* A portion of the transmitter signal is coupled into the AFC mixer and is heterodyned with the local oscillator signal. If the transmitter and the receiver are correctly in tune, the resultant difference frequency will be at the correct IF. However, if the receiver is not in tune with the transmitter, the difference frequency will not be correct.

Any deviation from the correct IF signal is detected by the AFC frequency discriminator, which, in turn, generates an error voltage. The error voltage magnitude is proportional to the deviation from the correct IF, and the polarity determines the direction of the error. The error voltage corrects the frequency of the local oscillator common to both the receiver mixer and the AFC mixer Many of the newer radar systems eliminate the requirement for the AFC system by fusing a special coherent frequency generator system.

The base frequency is much lower than the transmitted frequency and is multiplied and mixed at different levels. Since the local oscillator signal is picked off at the appropriate level, it is locked to the transmitter frequency without an AFC system. This also allows frequency diversity and agility with each transmitted pulse, which an AFC circuit could not track.

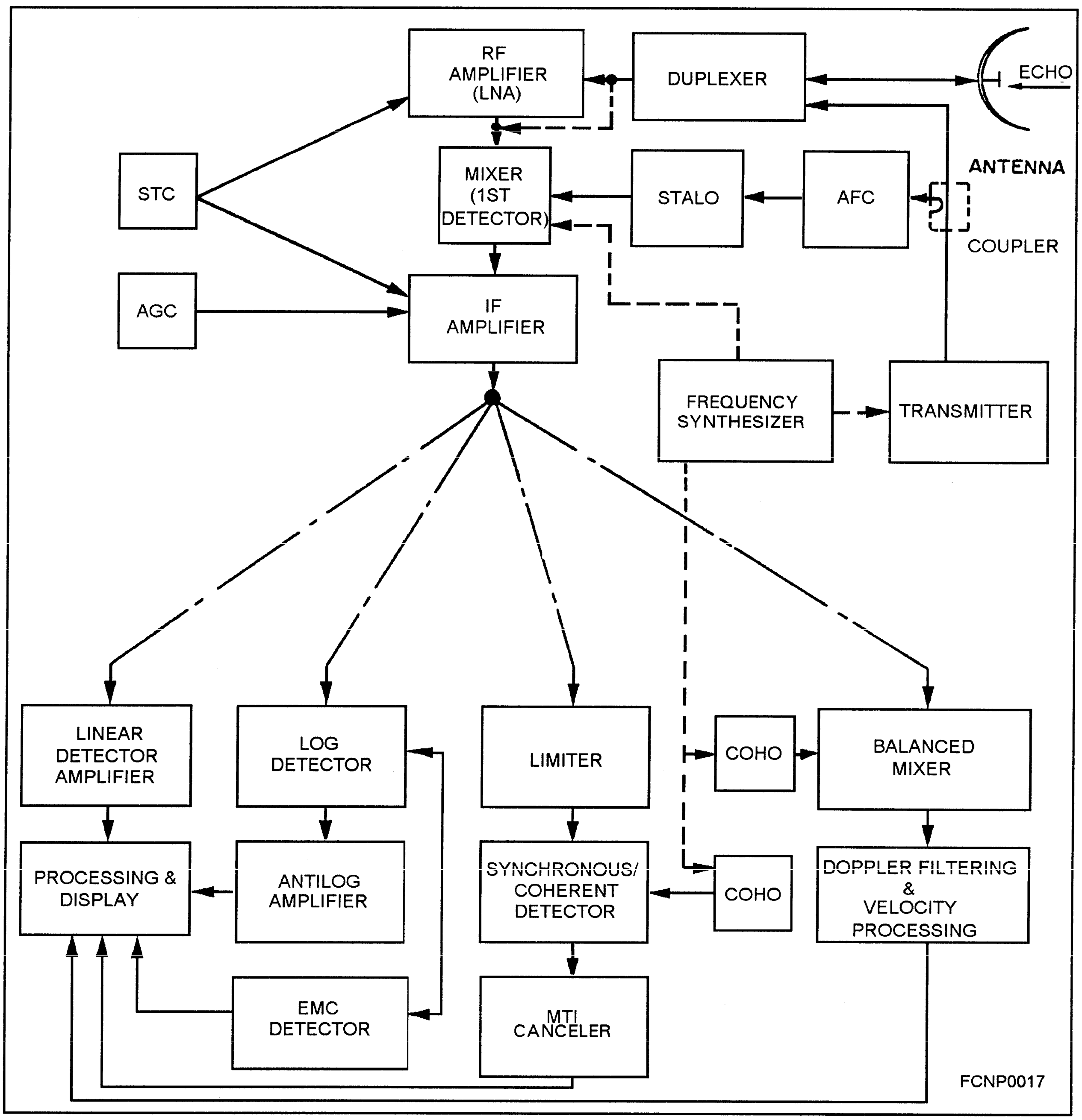

Figure 2-11.—Radar receiver general functions.

Local Oscillators

Most radar receivers use a 30- or 60-MHz intermediate frequency. A highly important factor in receiver operation is the tracking stability of the local oscillator, which generates the frequency that beats with the incoming signal to produce the IF. For example, if the local oscillator frequency is 3000 MHz, a frequency shift of as much as 0.1 percent would be a 3-MHz frequency shift. This is equal to the bandwidth of most receivers and would cause a considerable loss in gain. Bandwidth is the inverse of the pulsewidth, with a wider bandwidth for narrow pulses.

In receivers that use crystal mixers, the power required of the local oscillator is small, only 20 to 50 milliwatts in the 4000-MHz region. Because of the very loose coupling, only about 1 milliwatt actually reaches the crystal.

Another requirement of a local oscillator is that it must be tunable over a range of several megahertz to compensate for changes in both the transmitted frequencies and its own frequency. It is desirable that the local oscillator have the capability of being tuned by varying its voltage.

Because the reflex klystron meets these requirements, it is used as a local oscillator in some radar receivers. As the local oscillator in a microwave receiver, a reflex klystron need not supply large amounts of power, but it should oscillate at a frequency that is relatively stable and easily controlled.

The need for a wide electronic tuning range suggests the use of a voltage mode of a high order. However, if a mode of an excessively high order is selected, the power available will be too small for local oscillator applications, and a compromise between wide range and power is necessary. Also, the use of a very- high-order mode is undesirable because the noise output of a reflex klystron is essentially the same for all voltage modes. Thus, the closer coupling to the mixer required with high-order, low-power modes increases the receiver noise figure. Usually, the 1-3/4- or 2-3/4-voltage mode is found suitable. Since the modes are not symmetrical, the point of operation is usually a little below the resonant frequency of the cavity. This makes possible tuning above the operating frequency to a greater degree than if the precise resonant frequency is used.

In practice, the reflex klystron is used with an automatic frequency-control circuit. Since the repeller voltage is effective in making small changes in frequency, the AFC circuit is used to control the repeller voltage to maintain the correct intermediate frequency. It should be noted that the coarse frequency of oscillation is determined by the dimensions of the cavity, and there is, on most reflex klystrons, a coarse frequency adjustment, which varies the cavity size.

Reflex klystrons are also used as drivers for RF power amplifier klystrons. When they are used as drivers, the frequency and the amplitude stability are much more critical. Any variation in driver frequency is reproduced in the power amplifier output and, thus, on the target echo signal. This frequency-modulation (FM) variation can result in degraded Doppler tracking and velocity computations. If the FM deviation is large enough or if the driver is not operated at the peak of a mode, then amplitude variations will occur. This amplitude modulation (AM) may be very small in magnitude on the driver signal, but after a gain of 30 dB or more in the power amplifier, the magnitude can be considerable.

Both FM and AM signals are undesirable and are classified as noise. Therefore, extra care in tuning and maintenance of the power supplies is required to minimize FM and AM noise generation.

Frequency Synthesizers

Local oscillator configurations vary considerably, depending on the requirements of the individual radar system (the alternate system is shown by dotted lines in figure 2-11). MTI, pulse-Doppler, and CW-Doppler radars require close control over the phase and the frequency of the local oscillator to provide coherent detection. Pulse-compression radar receivers also require close frequency and phase control for their form of coherent detection. A frequency synthesizer system (instead of STALO) is becoming more common in radar systems. A radar with frequency agility for each pulse-repetition interval eliminates range ambiguities caused by target echoes returning after the next pulse interval begins.

Other frequency synthesizers use banks of crystals whose outputs are mixed in various combinations, then multiplied together to makeup the different base frequencies and multiplied by harmonic amplifiers and phase-lock loops similar to those shown in figures 2-12, a frequency synthesizer, and 2-13, a phase-lock loop. Although these are not the only possible configurations, they are representative of how frequencies can be produced for radar transmitters and receivers.

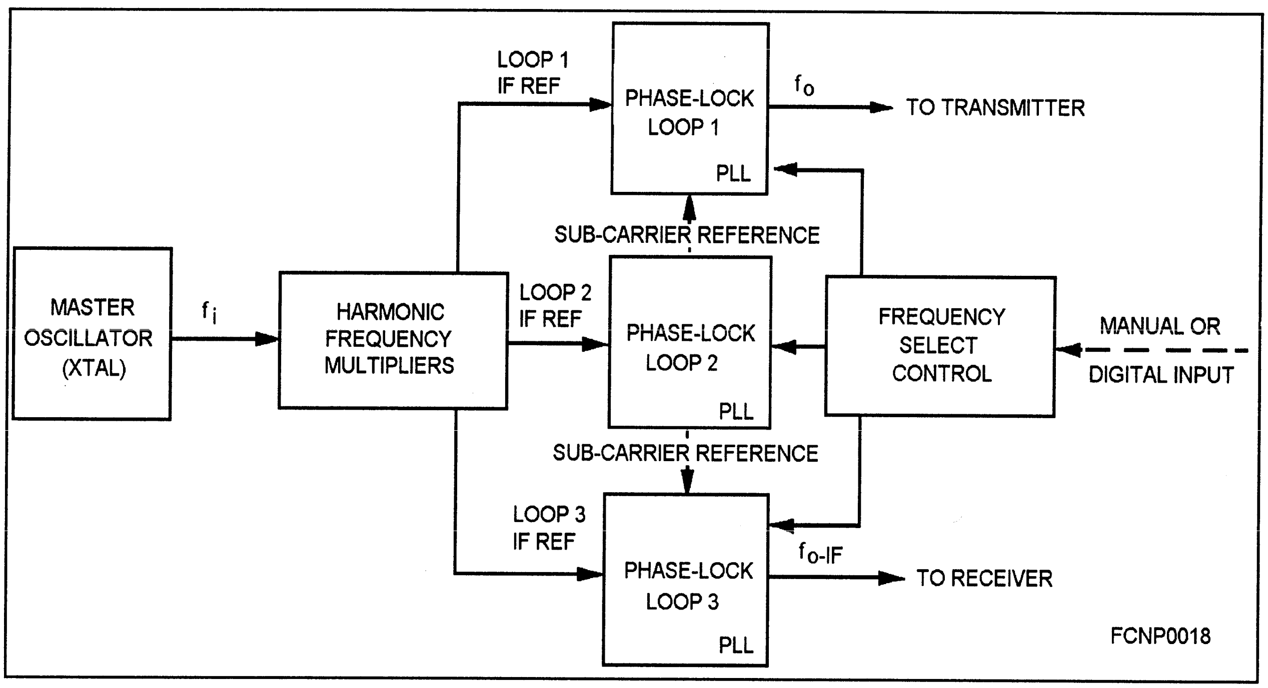

Figure 2-12.—Frequency synthesizer.

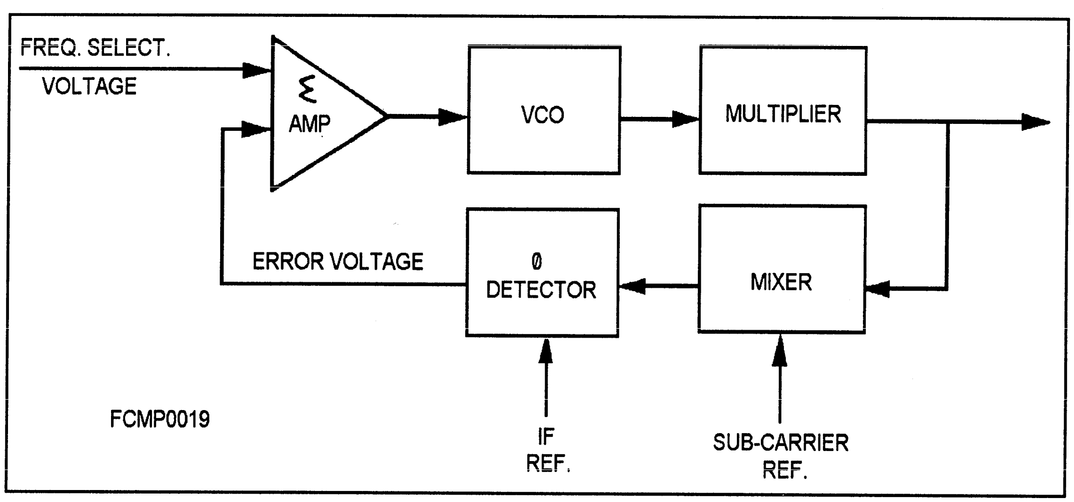

Figure 2-13.—Phase-lock loop.

Radar Receiver Mixers

Many radar receivers do not use the RF amplifier stage; instead, they use a crystal mixer stage as the receiver front end. If an RF amplifier is used, the design is critical, because the weak signal levels may easily be masked by noise generated by components in the RF amplifier. LNAs have solved some of the noise problems, but they are not in wide use in radar applications.

The simplest type of radar mixer is the single-ended, or unbalanced, crystal mixer. The mixer uses a tuned section of coaxial transmission line that is one-half wavelength long and matches the crystal to the signal echo and the local oscillator (LO) inputs. Local oscillator injection is accomplished by a probe, while the signal is injected by a slot in the coaxial assembly. This slot is normally inserted in the duplexer waveguide assembly and properly oriented to provide coupling of the returned signal. In this application, the unwanted signals at the output of the mixer (the carrier, the local oscillator, and the sum of these two signals) are effectively eliminated by a resonant circuit tuned to the intermediate, or difference, frequency.

One advantage of the unbalanced crystal mixer is its simplicity. It has, however, one major disadvantage —its inability to cancel LO noise. Since a klystron generates a high degree of noise, it makes it difficult to detect weak signals if that noise is allowed to pass through the mixer along with the signal.

One type of mixer that cancels LO noise is the balanced hybrid mixer (sometimes called the *magic T)*, shown in figure 2-14. In hybrid mixers, crystals are inserted directly into the waveguide one-quarter wavelength from their respective short-circuited waveguide ends. This is a point of maximum voltage along a tuned line. The crystals are also connected to a balanced transformer, the secondary of which is tuned to the desired IF.

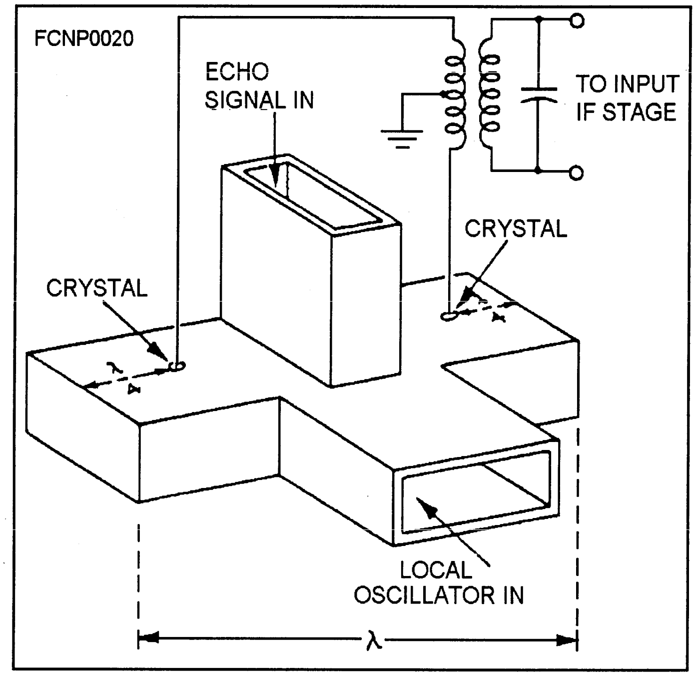

Figure 2-14.—Balanced hybrid crystal mixer.

Since there is a difference in phase between echo signals applied across the two crystals, and because the signal applied to the crystals from the LO is in phase, there will be a condition when both signals applied to crystal number 1 will be in phase, and the signals applied to crystal number 2 will be out of phase. This means that an IF signal of one polarity will be produced across crystal number 1, and an IF signal of the opposite polarity will be produced across crystal number 2. When these two signals are applied to the balanced output transformer, they will add. Outputs of the same polarity will cancel across the balanced transformer.

It is this action that eliminates the LO noise. Noise components that are introduced from the LO are in phase across the crystals and are canceled in the balanced transformer. It is necessary that the RF admittances of the crystals be nearly equal or the LO noise will not completely cancel. Only the noise produced by the LO is canceled; noise arriving with the echo signal is not affected.

IF Amplifiers

The IF section of a radar receiver determines the receiver's gain, signal-to-noise ratio, and effective bandwidth. The IF amplifier stages must have sufficient gain and dynamic range to accommodate the expected variation of echo signal power. They must also have a low-noise figure and a bandpass wide enough to accommodate the range of frequencies associated with the echo pulse.

The most critical stage of a radar receiver's IF section is the input, or first, stage. The excellence (figure of merit) of this stage depends on the noise figure of the receiver and the performance of the entire receiving system with respect to the detection of small objects at long ranges. Not only must gain and bandwidth be considered in the design of the first IF stage, but also, and perhaps of more importance, noise generation in this stage must be low.

Noise generated in the input IF stage will be amplified by succeeding stages and may exceed the echo signal in strength. The IF stages succeeding the first stage usually achieve higher gain because the signal level has been sufficiently increased by the low-noise input stage to preclude problems caused by noise generation.

A commonly used IF circuit is the single-tuned amplifier. Each stage has only one tuning adjustment. Inductance is varied until resonance between it and the total shunt capacitance of the stage occurs at the desired IF.

The IF stages require a wide bandwidth to accommodate the many frequencies that form the echo pulse. Insufficient bandwidth results in transient distortion, which is the inability of the stages to amplify transients linearly. Transient distortion may result in ambiguities in the range of the target because of the nonlinear rise of the leading edge of the reproduced echo pulse.

The cascading of amplifier stages to achieve the high gain required in microwave IF amplifiers results in an overall bandwidth reduction. To compensate for this effect, the bandwidth of separate stages must be increased. This may be accomplished by several methods, but we will only mention stagger tuning in this chapter. For further information on these methods, consult the appropriate operating procedures for your fire-control system.

In the stagger-tuning method, the resonant frequencies of the various stages combine so that together they pass the frequency band to be amplified. The product of each stage's amplitude response curve forms the overall response curve.

Gain Controls

Sensitivity time control (STC) and automatic gain control (AGC) are commonly used to control the gain of IF amplifiers. STC may even be used in RF amplifier stages of some radar receivers. Radars detect targets of a wide variety of sizes, ranges, and reflective area, which produce a wide range of echo signal amplitudes that may exceed the dynamic range of a fixed gain receiver.

SENSITIVITY TIME CONTROL.— Sensitivity time control (STC) is used to control the gain of a radar receiver as a function of range. Close-in target echoes and clutter return are of greater amplitude than when they are at greater ranges. Using STC tends to equalize the amplitude of echoes independent of range. There are several methods of STC, from the simple resistance/capacitance (RC) time constant to the more-elaborate digital schemes. The digital STC may be controlled by a computer to provide optimum gain as a function of range.

AUTOMATIC GAIN CONTROL.— Automatic gain control (AGC) is common in most receiving systems, whether radar or communications. The AGC circuit detects the output from the IF amplifier and produces a voltage proportional to the strength of the detected signal and noise. For a close-in strong target return, a larger AGC voltage is produced and the overall receiver gain is reduced, thereby producing the optimum signal strength out of the amplifier. This closes the AGC loop and produces a relatively constant amplitude signal out of the IF amplifier, independent of range.

Logarithmic IF Amplifiers

When radars are operated where interference and clutter are encountered or where jamming may occur, techniques can be used to adjust the receiver sensitivity as the interference varies in intensity. Digital processing uses a threshold criteria similar to that where an operator adjusts the sensitivity to the point where interference is just barely detectable. This is the process of constant false-alarm rate (CFAR) when the radar receiver makes the adjustments automatically. Logarithmic amplifiers rely on the CFAR principle to amplify signals that exceed a certain threshold and provide only unity gain for those below the threshold. The threshold is automatically adjusted to maintain the same false-alarm rate.

Logarithmic IF amplifiers are widely used in electronic attack (EA) receivers and monopulse angle-tracking channels. They are also used in digital pulse compression and phase detection.

Detectors

The detector in a basic radar receiver converts the IF signal into a video signal to be displayed and/or processed for tracking. There are many forms of detection, and they vary depending on the type of radar and method of coherency used.

Detectors include linear (diode) detectors, logarithmic detectors, and phase-sensitive detectors.

LINEAR (DIODE) DETECTORS.— The simplest form of detectors, and still commonly used, are the diode detectors. They are classified as linear detectors because their output is directly proportional to the input.

LOGARITHMIC DETECTORS.— The logarithmic detectors, commonly called *log detectors,* have outputs proportional to the logarithm of the IF envelope input. Logarithmic detectors are fairly common in EA receivers. They usually have multiple stages where the overall gain varies logarithmically.

PHASE-SENSITIVE DETECTORS.— A synchronous/coherent detector for MTI was shown in figure 2-11. This type of detector has several possible configurations, based on the type of signal desired as an output.

A phase (0) detector is one form of synchronous/coherent detector; it has an output that has only phase information. A synchronous detector has both phase and amplitude information in its output. A balanced mixer has phase, amplitude, and frequency information in its output.

Phase-sensitive detectors (0 detectors) are key elements in MTI radars. The 0 detector detects the phase-shift information caused by a moving target. The detector receives inputs of the IF signal and the COHO signal, and it produces a video signal whose amplitude and polarity varies with phase differences only.

The 0 detector can be used in monopulse-tracking radar receivers to determine the angular error of the target from the boresight center. Two identical receiver channels are required to provide azimuth and elevation error detection. The angle channel phase is compared to the range channel reference phase to produce a signal, whose amplitude and polarity indicate the amount and direction of phase error, which is directly related to the angle offset.

A synchronous detector can provide the same information as a phase detector in monopulse radars. The difference is that the phase comparison determines the polarity of the output signal only, while the amplitude comparison determines the amount of error.

A balanced mixer is more suited for use in CW and Doppler signal processing since frequency information is also contained in the output of balanced mixers. This signal is then fed to the filter bank for Doppler shift detection.

Pulse Compressions

Pulse compressions are used to increase the transmitted average power while retaining the range resolution of a narrow pulsewidth. Many fire-control and search radars use pulse compression. Pulse-compression radar has additional advantages over normal pulse radar—it has better discrimination of target echoes in clutter and is less susceptible to jamming.

Two basic types of pulse compression are linear FM and phase coding. Both encode the transmitted pulse with information that is compressed (decoded) in the receiver of the radar. Radars that use pulse compression can compress pulses with durations of many microseconds down to a tenth of a microsecond.

The ratio of transmitted pulsewidth to compressed pulsewidth is called the *pulse-compression ratio.* Ratios of up to 160:1 are currently in use.

PHASE-CODED PULSE COMPRESSIONS.— Phase coding the transmitted pulse involves shifting the phase of the transmitter RF during the pulsewidth. A binary code is the normal method used to determine the phase shift. With a binary code, the binary bits can determine if the signal will be shifted to an in-phase condition or a 1800 out-of-phase condition with respect to the reference. Pulse compression of the encoded waveform involves decoding the phase shifts and comparing this to the stored code.

By making a bit-by-bit comparison of the received signal to the transmitted signal, target detection can be determined at the point when the bits match. This type of circuit is known as a *matched filter.*

ANGLE-ERROR DETECTIONS.— With tracking radars that use phase-coded pulse compression, extraction of the angle error is also required. Monopulse radar receiver angle-error information is contained in the phase difference between the sum (range) and difference (angle) channels. Before the phase difference can be determined, the phase coding must be removed.

The IF signal from both angle channels and range channels is equalized in IF limiters (log-IF amplifiers). The phase coding is removed by switching the output phase of the signal decoder with the binary phase code during the range gate interval. Phase-coded IF signals in correspondence with the range gate and the binary phase code will produce a decoded signal. Signals more than 1 bit out of correspondence will have their code changed.

The decoded signal will then be fed to the narrowband filter. The decoded signals have a much narrower bandwidth than phase-coded signals and pass through the narrowband filter. The narrowband filter will ring when a decoded signal passes through and produce a signal.

The output signal is then fed to a limiter to maintain equal signals in all three channels. The reference phase of the range channel is compared to the angle channel in a phase-sensitive detector. The output of the phase-sensitive detector is a dc voltage representing the amount and direction of the phase error. The angle-error voltage is then processed to correct the antenna/director pointing error.

Figure 2-15 shows the basic process required to extract the angle-error information.

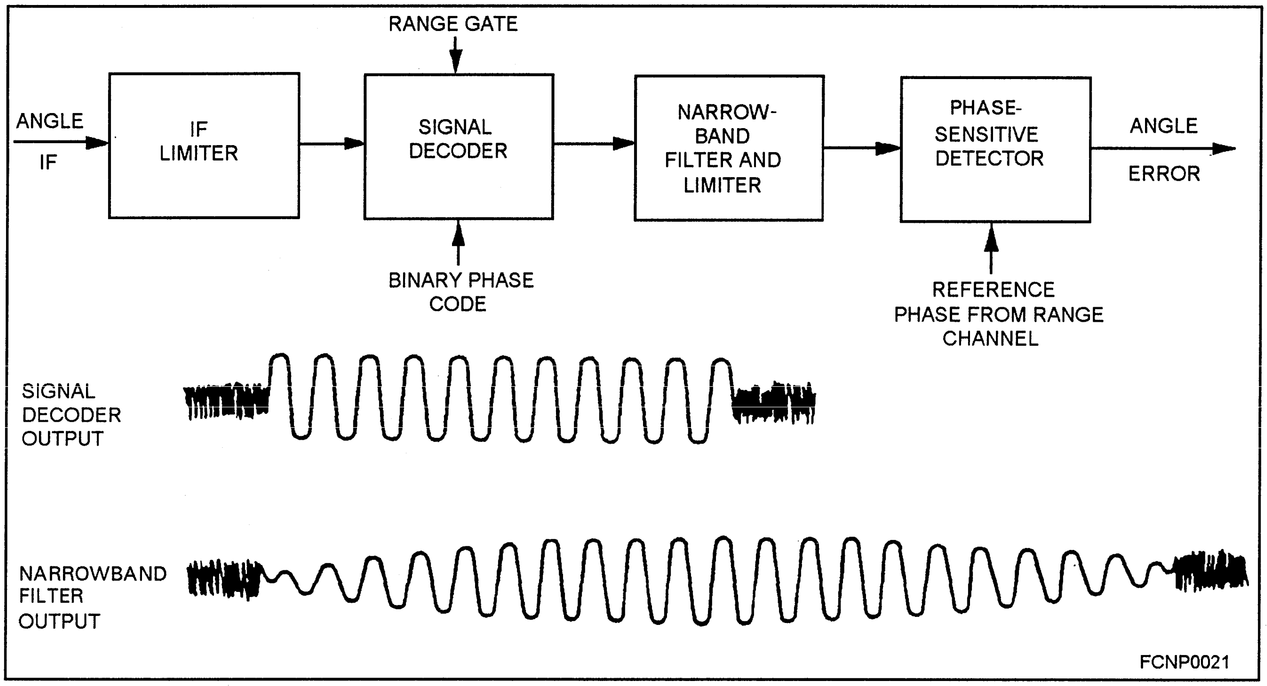

Figure 2-15.—Angle-error detection with phase-coded pulse compression.

RADAR DISPLAYS

Most radars that Fire Controlmen operate and maintain have one or more displays to provide information about the area the radar is searching or the targets being tracked. The usual display is a CRT that provides a combination of range, bearing (azimuth), and/or elevation data.

Some displays provide raw data in the signal from the radar receiver, whereas others provide processed information in symbology and alphanumerics.

RECOMMENDED READING LIST

> **NOTE:** Although the following references were current when this TRAMAN was published, their continued currency cannot be assured. Therefore, you need to ensure that you are studying the latest revision.

Microwave Principles, Module 11, Navy Electricity and Electronics Training Series, NAVEDTRA 172-11-00-87, Navy Education and Training Program Management Support Activity, Pensacola, FL, 1987.

Radar Principles, Module 18, Navy Electricity and Electronics Training Series, NAVEDTRA 172-18-00-84, Navy Education and Training Program Development Center, Pensacola, FL, 1984.*

* Effective 1 September 1986, the Naval Education and Training Program Development Center became the Naval Education and Training Program Management Support Activity.